Blind Adaptation of Partial Response Equalizers for 200Gb/s per Lane IM/DD Systems

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Abstract *We propose a novel non-data-aided adaptation algorithm for a partial-response feed-forward equalizer. Performance is evaluated based on 224Gb/s PAM4 signals captured after 0km and 20km O-band transmission suitable for hyper-scale datacenter intra-connections.*

Introduction

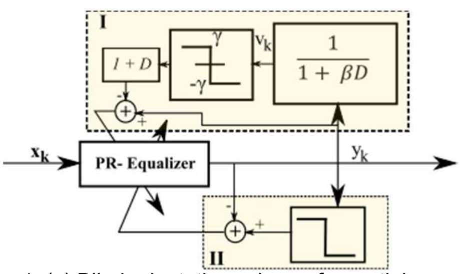
Intra datacenter connectivity is currently dominated by pluggable modules employing intensity modulation / direct detection (IM-DD) technology for cost and power efficiency. 400GbE connectivity is realized employing four lanes of 4-level pulse amplitude modulation (PAM4) with 100Gb/s per lane. Specifications for 800Gb/s modules have also been proposed employing 100Gb/s as well as 200Gb/s per lane with PAM4[1, 2].

Receivers based on powerful digital signal processing (DSP) have recently gained popularity in short-reach IM-DD systems since channel-induced distortions can be mitigated employing digital equalizers. To minimize power consumption, DSP is usually performed at 1 sample per symbol (1sps). In the presence of severely bandwidth-limited channels, full-response (FR) equalization is not an optimal choice because it leads to strong noise enhancement[3]. Noise whitening can be achieved either by a post-filter after a FR equalizer or by a partial response (PR) equalizer. Finally, maximum-likelihood sequence estimation (MLSE) can be realized using a Viterbi equalizer. In [3], the authors have compared several modulation formats and equalization schemes for an IM/DD system and concluded that for data-rates up to ~224Gb/s per lane and accumulated dispersion of ~17ps/nm, PR equalization followed by MLSE results in the best performance. To maximize power efficiency, and ensure interoperability and system simplicity, equalization and data recovery in IM/DD systems are realized in blind mode. However, in blind mode the initial convergence of PR equalizers can be challenging, especially if the signal is not sampled at the optimal instant.

In this article, we propose an algorithm for the initial convergence and tracking of non-data-aided PR equalizers operating at 1sps. We evaluate the performance of the proposed algorithm by offline processing of experimental data captured in back-to-back configuration and after transmission over 20km of standard single-mode fiber (SSMF) in O-band, for a single-carrier 224Gb/s PAM4 signal (112GBd). The results demonstrate the robustness of the proposed scheme for high bit-rate IM/DD systems in strong ISI scenario.

Equalizer convergence in blind mode

The proposed scheme is composed of two steps, I) Initial convergence based on the Sato blind adaptation algorithm [4], and II) Error minimization by decision-directed least mean square (DD-LMS) algorithm. A duobinary or 1+D response is chosen as the target output of the PR-equalizer. The block diagram of the proposed algorithm is shown in Fig. 1(a). Here $\mathbf{x}_k$ is the distorted and noisy tap content vector of the T-spaced PR equalizer and y_k is the corresponding output sample. During the initial convergence step (I), y_k is first converted to FR output by applying the transformation $v_k = y_k - \beta v_{k-1}$, where v_k is a constant in range $0 \le \beta < 1$. In case the equalizer target is a duobinary signal, β is close to 1 (but



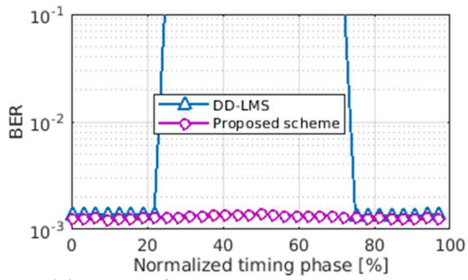


Fig. 1: (a) Blind adaptation scheme for partial response equalizers, (b) BER performance with varying timing phase

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not exactly 1 to avoid instability). Next v_k is sliced to a value of ±γ where γ is a constant defined as $\gamma = E[{a_k}^2]/E[|a_k|]$ with a_k belonging to the transmitted symbol set, i.e. {±1, ±3} for PAM4, and *E[·]* is the expectation operator. The output of the slicer is then passed through a duobinary (1+D) filter and is subtracted from y_k to get the error signal, i.e. $\varepsilon_k = y_k - \gamma.\mathrm{sign}[v_k]$. The equalizer coefficients ($\mathbf{c}_k$) are iteratively adapted via $\mathbf{c}_{k+1} = \mathbf{c}_k - \mu\varepsilon_k\mathbf{x}_k$, where μ is the adaptation step size. After achieving initial convergence, the equalizer adaptation is switched to step-II where y_k is first sliced to the seven-level signal corresponding to duobinary PAM4. Equalizer output is then subtracted to calculate the error term which is used for further mean squared error (MSE) minimization. If the equalizer contains nonlinear taps, as is the case in a Volterra equalizer for nonlinearity mitigation, the adaptation of the nonlinear taps is switched off during step I) and enabled at stage II). As discussed above, the output of the equalizer goes through a MLSE block for data recovery.

Fig. 1(b) shows the BER versus timing phase (normalized to the symbol period) of the signal at the input of the equalizer. Due to the severe bandwidth limitation, an advanced timing recovery (TR) is necessary that assumes a short TR equalizer before the phase detector [5]. This equalizer normally works in blind mode and depending on channel conditions, clock frequency offset, and jitter, the normalized timing phase can either be at position 0% or 50% with a high probability. As demonstrated in Fig. 1(b), in case of DD-LMS based adaptation only, a correct timing phase of the input signal is crucial to achieve equalizer convergence. Successful convergence is achieved only if the timing phase of the signal is offset by at most ±21% relative to the optimal instant (i.e. 0%). On the other hand, employing the proposed scheme, equalizer convergence and BER are agnostic to the timing phase of the input signal.

Experimental evaluation, results and discussion

The block diagram of the experimental setup as well as the transmitter and receiver DSP steps are shown in Fig. 2(a). A pseudo-random quaternary sequence (PRQS) was generated and resampled to ~1.07sps to output a 112GBd signal when uploaded to an arbitrary waveform generator (AWG) operating at 120Gsamples/s. A pre-emphasis filter then followed, which compensated the end-to-end channel response. The target end-to-end channel response for the pre-emphasis filter was set to duobinary shaped 112GBd PAM4 signal, which minimized the peak-to-average power ratio (PAPR) enhancement and hence resulted in optimal performance. The waveform was then uploaded to an AWG whose output was electrically amplified before driving an electro-absorption modulator that modulated a distributed feedback laser at 1309nm, housed on the same chip (aka externally modulated laser (EML)). The modulated output went either directly to a variable optical attenuator (VOA) or after passing through 20km SSMF for back-to-back and transmission tests, respectively. The optical signal was then amplified by a semiconductor

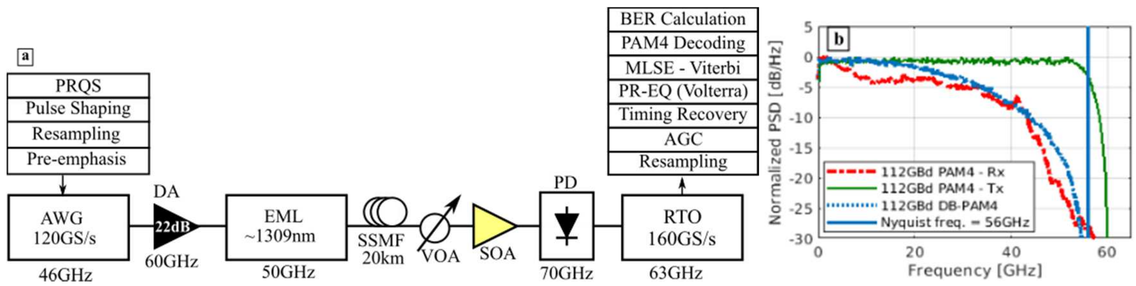

Fig. 2: (a) Experimental setup, (b) Comparison of PSD of transmitted, received and DB-PAM4 signals.

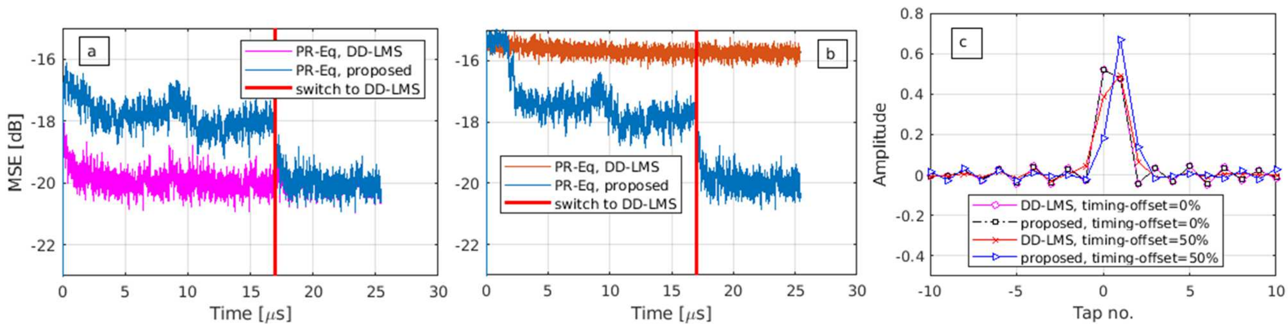

Fig. 3: MSE evolution during adaptation with timing-offset (a) 0% and (b) 50%. (c) Equalizer coefficients after adaptation.

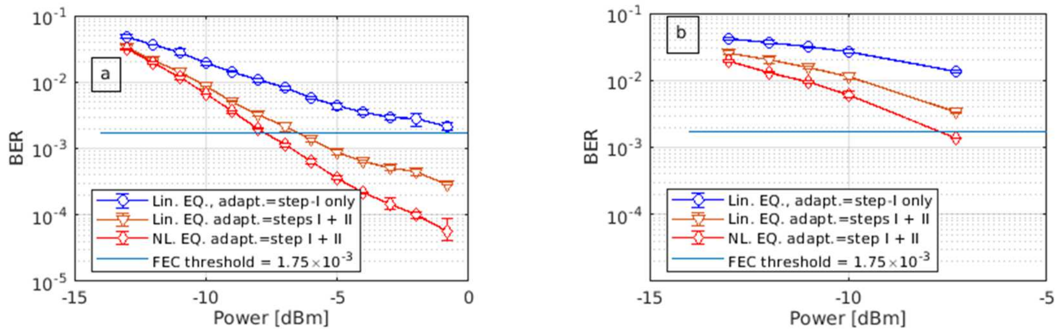

Fig. 4: BER vs received optical power in (a) back-to-back and (b) 20km SSMF transmission scenario.

optical amplifier (SOA) to a power of 7dBm and input to a photodetector (PD). The electrical output of the PD was sampled by an oscilloscope and processed offline. The receiver DSP steps included resampling, automatic gain control, TR, PR equalization targeting duobinary shape, MLSE, PAM4 demapping and finally BER calculation for performance evaluation.

Comparing the transmitted and received power spectral density (PSD), a spectral loss of >25dB is observed at the Nyquist frequency of 56GHz, highlighted by a vertical line in Fig. 2(b). As expected, the received signal PSD is close to the duobinary shape, resulting in minimal noise enhancement after the PR equalizer. The MSE evolution during the adaptation of the PR equalizer is shown in Fig. 3 (a) and (b) for different timing-offset of the input signal. In case the input is sampled at the optimal instant, DD-LMS quickly minimizes the MSE and achieves a value around -20dB (Fig. 3(a)). Employing the proposed algorithm for PR-equalizer adaptation, the MSE initially reduces and then oscillates around the value of -18dB. At ~17μs, adaptation switches to DD-LMS mode, as shown in Fig. 1(a). This results in further reduction in MSE which saturates at the same value as in case of DD-LMS only. The acquired PR equalizer taps are shown in Fig. 3(c). The resulting taps acquired by both schemes are very similar. In case the input signal is not optimally sampled, as depicted in Fig. 3(b) for timing-offset of 50%, DD-LMS alone fails to minimize MSE. On the other hand, the proposed scheme minimizes the MSE to roughly -18dB, which is the same as in the case of optimal signal sampling instant. Hence, initial convergence is successfully achieved during the step I of the proposed scheme. Further MSE reduction is then achieved by switching to DD-LMS. The acquired taps in this case are quite different for both schemes and are also depicted in Fig. 3(c).

The performance of the proposed scheme is further evaluated by processing experimental data with varying received optical power. The corresponding results are shown in Fig. 4(a) and (b) for back-to-back and 20km SSMF transmission, respectively. Equalizer adaptation employing only step I of the proposed scheme results in suboptimal performance and best BER of ~2×10^{-3} is reached at -0.8dBm received power in back-to-back scenario. This result is expected because step I provides good initial convergence but does not minimize MSE, as illustrated in Fig. 3. Employing both step I and step II for equalizer adaptation, BER improves about one decade to ~3×10^{-4}. In this case, the assumed FEC threshold BER of 1.75×10^{-3} is achieved at -6.8dBm in the back-to-back scenario. A further improvement in BER is achieved by employing 3rd order Volterra based nonlinear equalizer (memory of 9 and 7 symbols for 2nd and 3rd order taps, respectively). In this case the required power to reach the FEC threshold is improved by ~0.8dB. A similar trend is observed for the 20km SSMF transmission case as shown in Fig. 4(b). Due to the losses of fiber and connectors, the maximum available optical power after transmission was -7.3dBm. BER below FEC threshold is achieved only with nonlinear equalization. It is worth mentioning that apart from the power loss, no other penalties due to transmission were observed at the transmission wavelength of 1309nm.

Conclusion

In this article we propose a two-step adaptation approach for non-data aided partial-response equalizers suitable for severely bandwidth-limiting channel conditions. The proposed adaptation scheme operates at 1 sample per symbol for power efficiency in receiver DSP and is robust to the timing phase of the input signal. The performance of the proposed scheme is evaluated by successful processing of experimental data obtained in back-to-back configuration as well as after 20km SSMF transmission of a 112GBd (224Gb/s) PAM4 signal. The assumed FEC threshold (1.75×10^{-3}) is achieved at a received optical power of -7.5 dBm, demonstrating the feasibility of the scheme for large scale datacenter interconnects.

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